Bullet Impact on Steel and Kevlar®/Steel Armor - Experimental Data and Hydrocode Modeling with Eulerian and Lagrangian Methods

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Outline

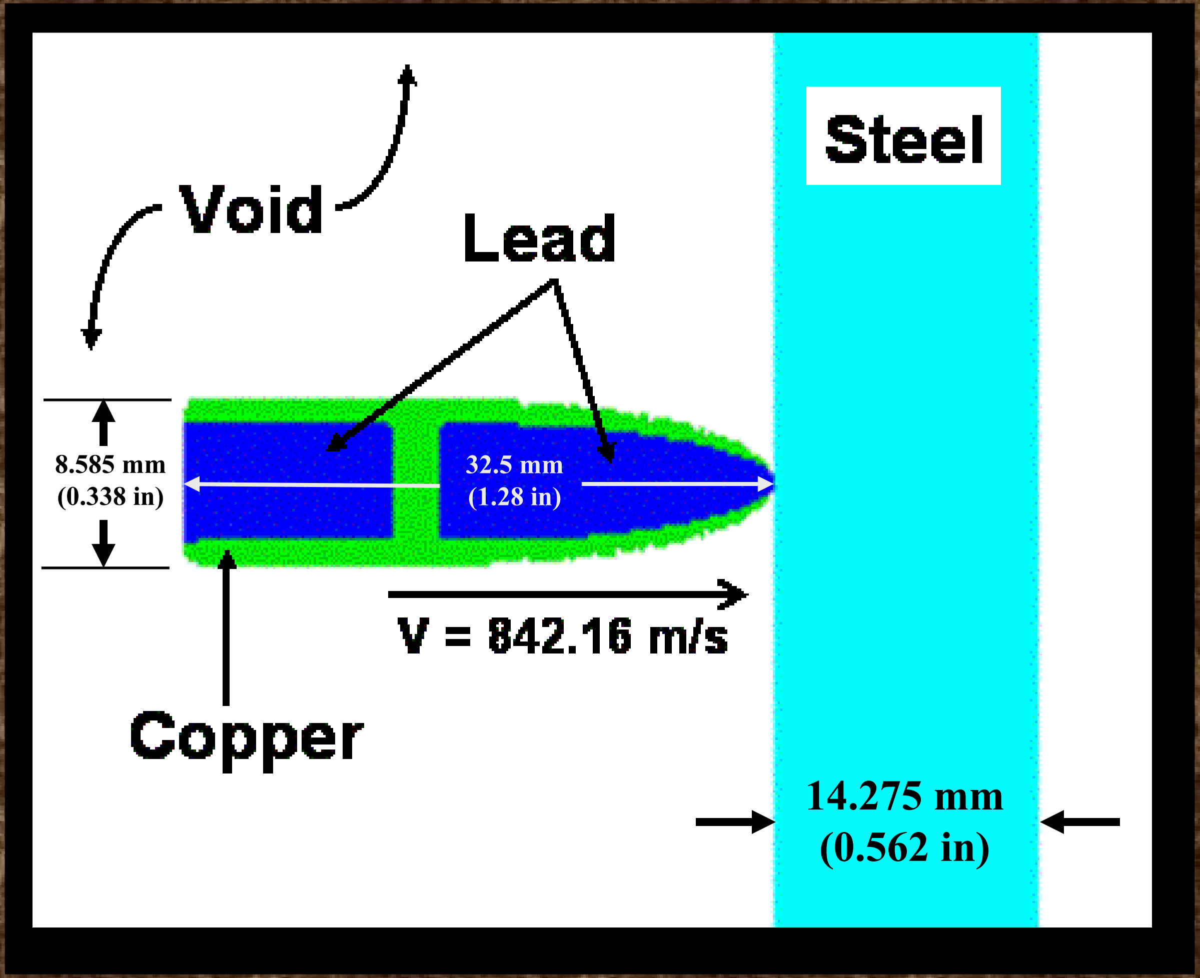
- Introduction
- AUTODYN Simulations
  - Lead/Copper Bullet Impact on Mild Steel
  - “ “ “ “ “ Kevlar®/Steel armor
- Ballistics Lab Experiments
  - Lead/Copper Bullet Impact on Mild Steel
  - “ “ “ “ “ Kevlar®/Steel armor
- Comments on Results
- Conclusions

Introduction

- Projectile: Lead/Copper Partitioned (A-Frame) Hunting Bullet
- .338 Winchester Magnum
- Chronographed Muzzle Velocities
  - 842.16 m/s (2763 ft/s) Mild Steel Impacts
  - 854.35 m/s (2803 ft/s) Armor Impacts
  - 16 tests: mean = 847.98 m/s (2782 ft/s)
    std dev = ±7.44 m/s (24.4 ft/s) = ±0.877 %
- Witness Plate: Mild Steel
- Armor: Kevlar® and Kevlar®/Steel

Bullet Penetration of Mild Steel

Geometry and Material Definition



Material Properties for Impact Simulations

Lead

Equation of State	Shock
Reference Density (g/cm^3)	11.35
Gruneisen Coefficient	2.77
Parameter C_1 (m/s)	2.051E03
Parameter S_1	1.46
Strength Model	Von Mises
Shear Modulus (KPa)	5.6E6
Yield Strength (KPa)	5.0E3

Copper

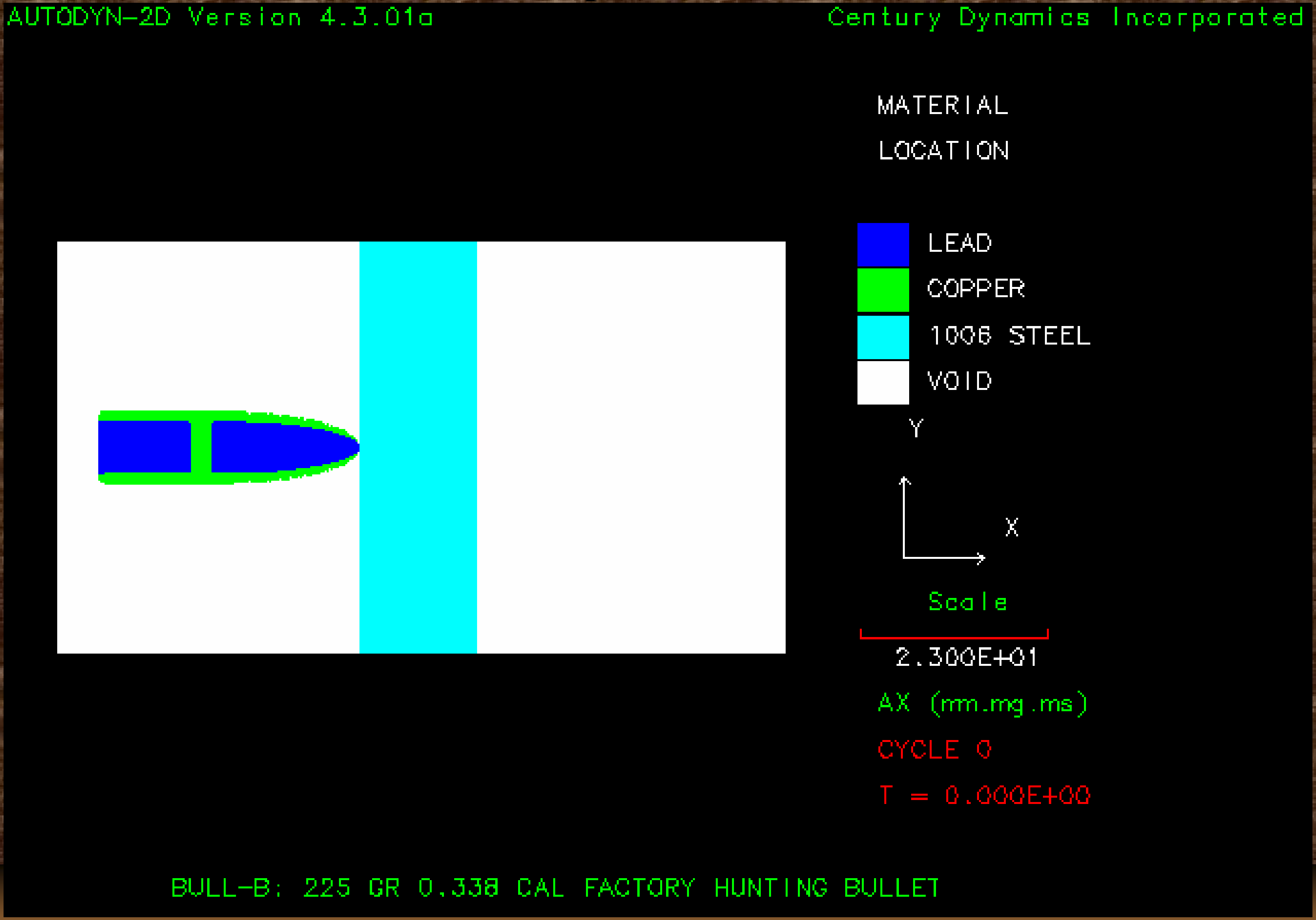
Equation of State	Shock
Reference Density (g/cm^3)	8.93
Gruneisen Coefficient	1.99
Parameter C_1 (m/s)	3.94E03
Parameter S_1	1.489
Strength Model	Von Mises
Shear Modulus (KPa)	4.5E7
Yield Strength (KPa)	7.0E4

Steel

Equation of State	Shock
Strength Model	Johnson-Cook
Reference Density (g/cm^3)	7.896
Gruneisen Coefficient	2.17
Parameter C_1 (m/s)	4.569E03
Parameter S_1	1.49
Reference Temperature (K)	300
Shear Modulus (kPa)	8.18E07
Yield Stress (kPa)	5.17106E05
Hardening Constant (kPa)	2.75E05
Hardening Exponent	0.36
Strain Rate Constant	0.022
Thermal Softening Exponent	1.0
Melting Temperature (K)	1.811E03

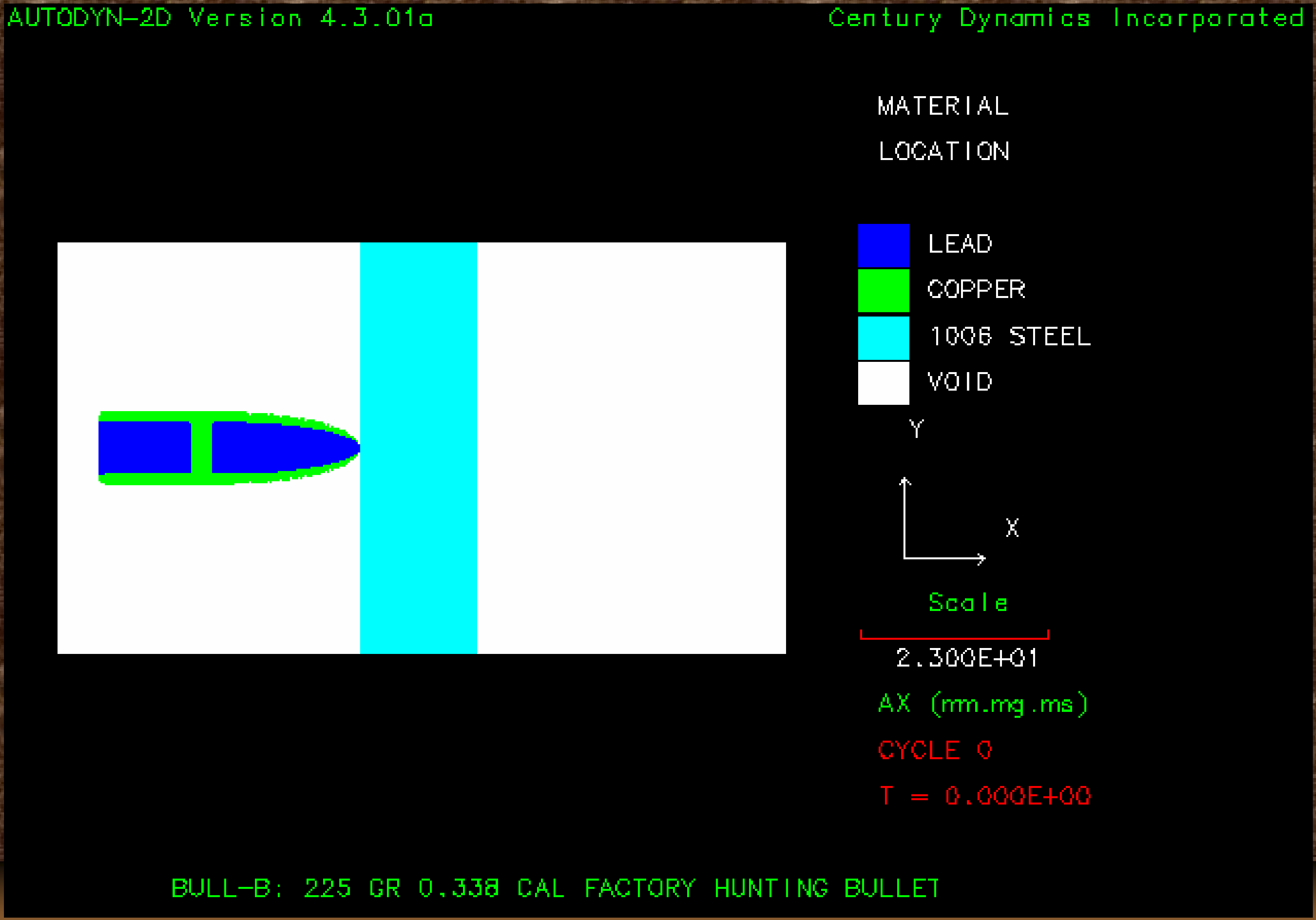
Lead/Copper Bullet Penetration of Mild Steel

Color Represents Pressure



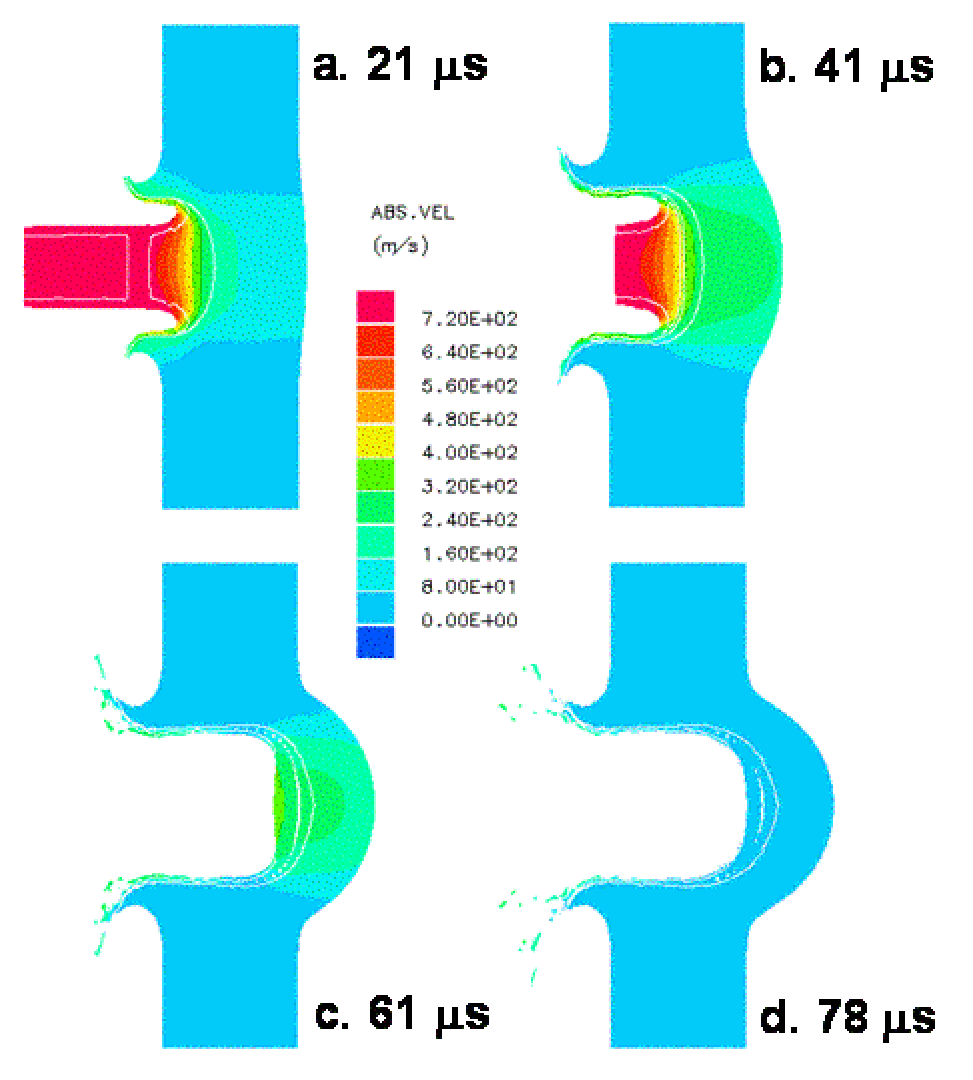
Lead/Copper Bullet Penetration of Mild Steel

Color Represents Absolute Velocity



Lead/Copper Bullet Penetration of Mild Steel

Color Represents Absolute Velocity



Lambert Equation for Projectile Penetration (Ballistic Limit)

$$V_l = \left(\frac{l}{d}\right)^{0.15}(4000)\sqrt{\left(\frac{d^3}{m}\right)\left(\left(\frac{t}{d}\right)Sec^{0.75}\theta + e^{-\left(\frac{t}{d}Sec^{0.75}\theta\right)} - 1\right)}\left[\frac{m}{s}\right]$$

Where:

l	=	Projectile length	= 3.25 cm
d	=	Projectile diameter	= 0.8585 cm
m	=	Projectile mass	= 14.578(g)
t	=	Target thickness	= 1.427 cm
θ	=	Impact Angle	= 0.0 deg

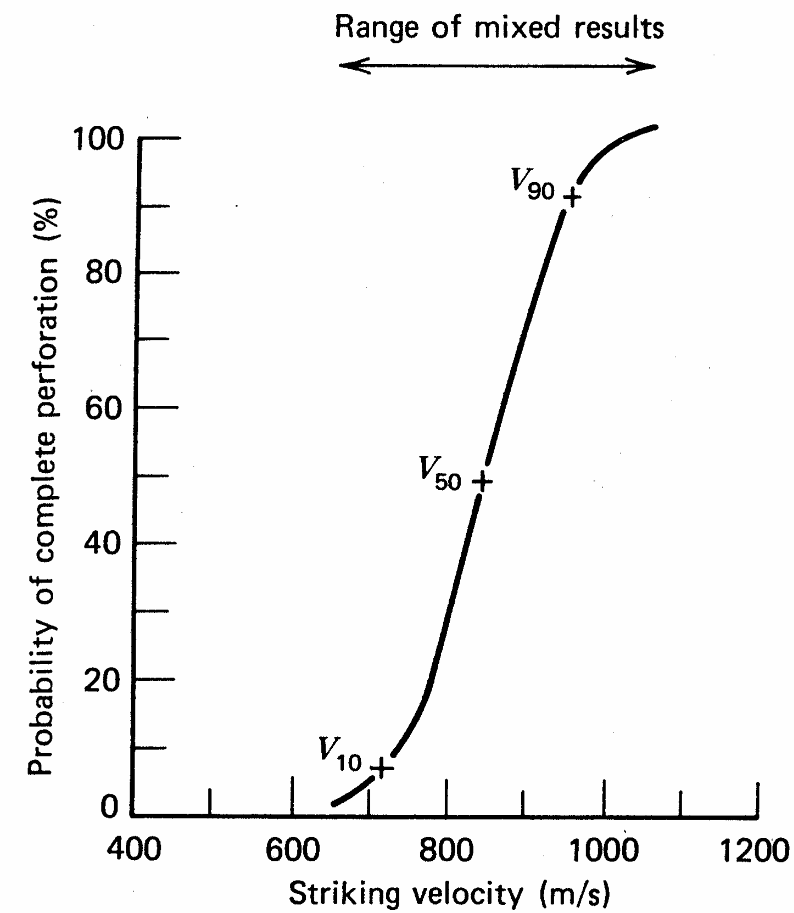
$$V_l = 939.12\frac{m}{s}$$

Compared to 848 m/s => almost penetrates

Ref: ***Introduction to Terminal Ballistics*** **– Course Notes, Donald R. Carlucci, 2004**

Ballistic Limit

Typical Experimental Results



Ref: *Impact Dynamics*, Zukas et al

$$V_l = V_{50}$$

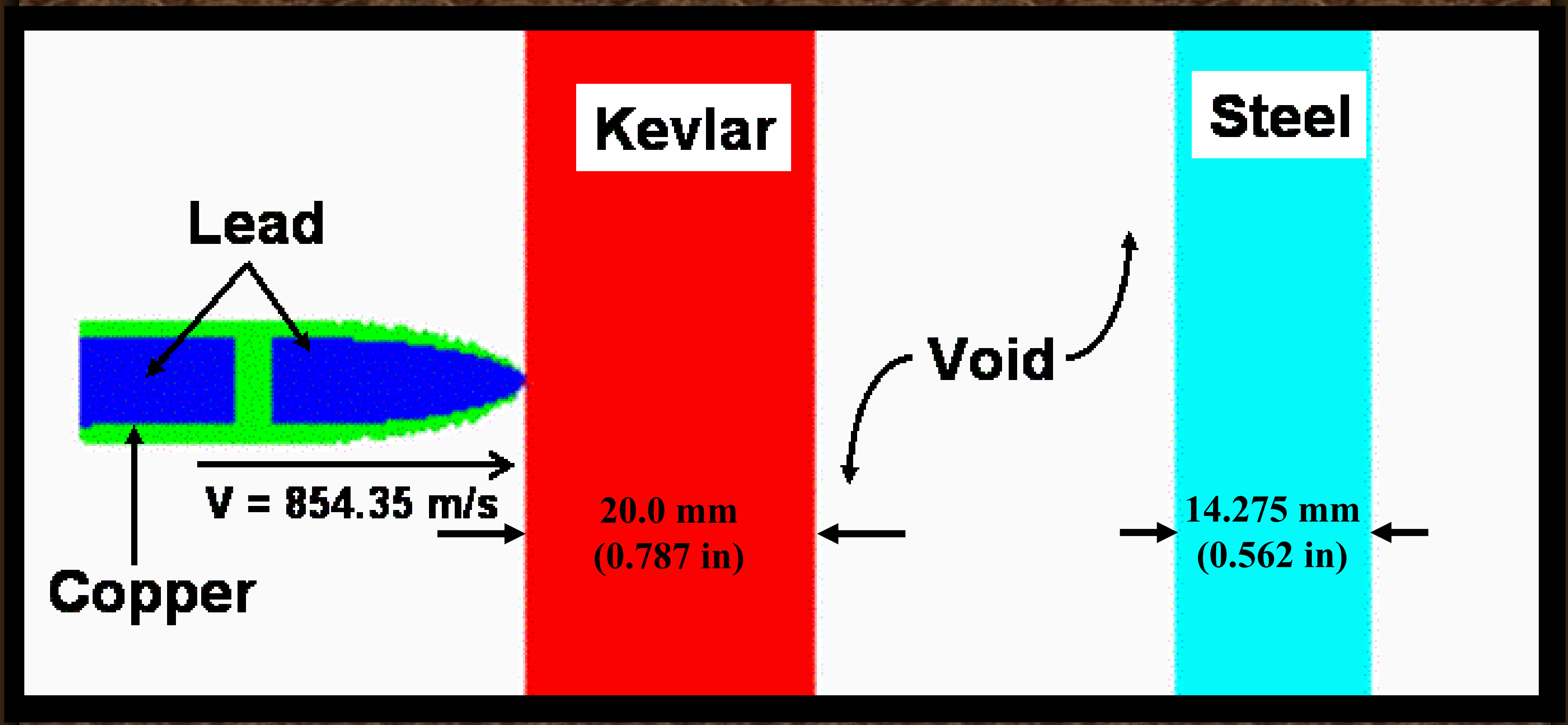
Material Properties for Impact Simulations (Cont)

Kevlar®	
Equation of State	Puff
Reference Density (g/cm^3)	1.29
Parameter A_1 (kPa)	8.21E06
Parameter A_2 (kPa)	7.036E07
Parameter A_3 (kPa)	0.0
Gruneisen Coefficient	0.35
Expansion Coefficient	0.25
Sublimation Energy (J/Kg)	8.23E06
Parameter T_1 (kPa)	0.0
Parameter T_2 (kPa)	0.0
Reference Temp (K)	0.0
Specific Heat (C.V.) (J/kgK)	0.0
Strength Model	Von Mises
Shear Modulus	3.0E7
Yield Strength	3.0E5
Tensile Strength	-2.6E5

Lead/Copper Bullet Penetration of Kevlar and Mild Steel

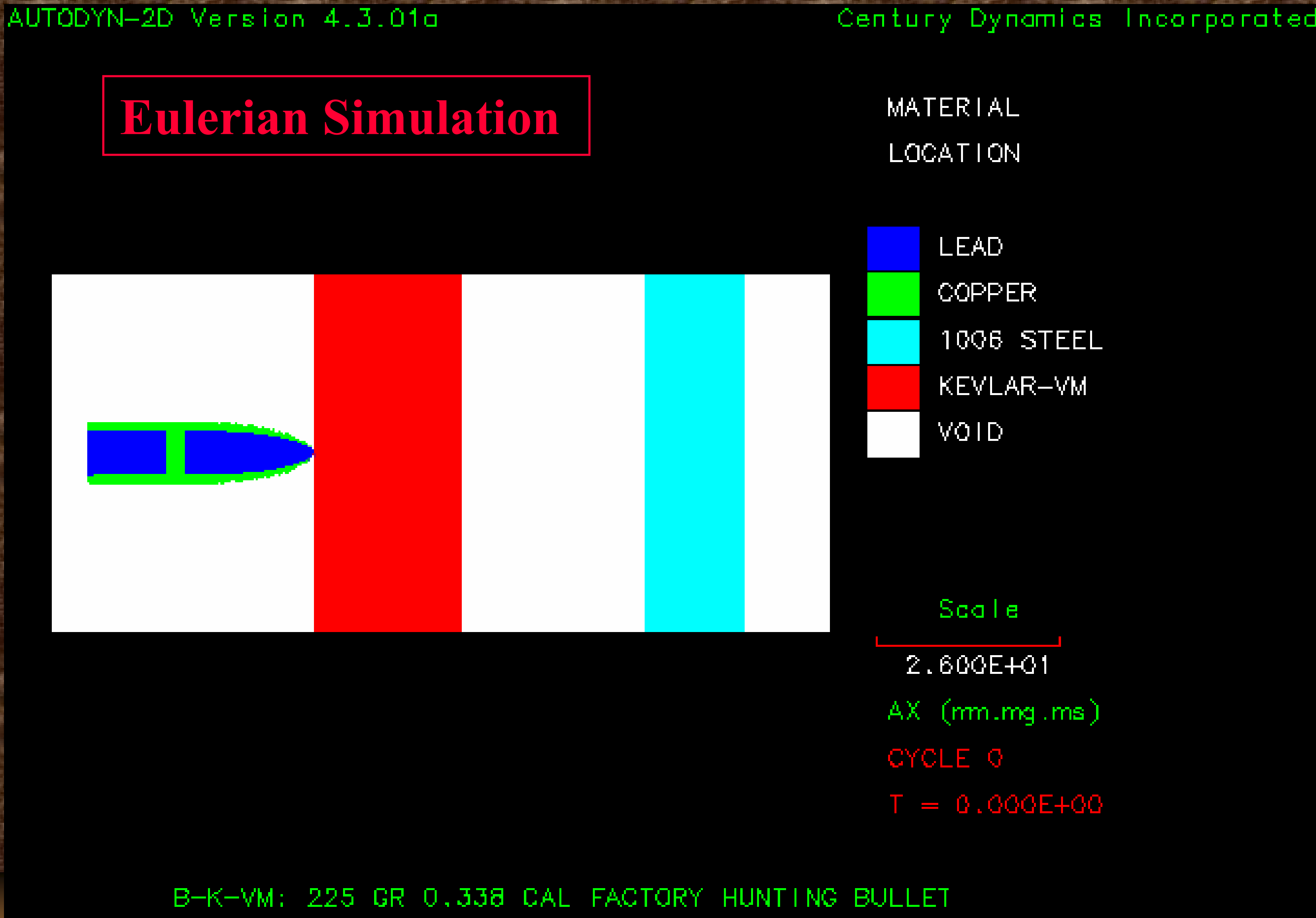
Geometry and Material Definition

Eulerian Simulation



Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

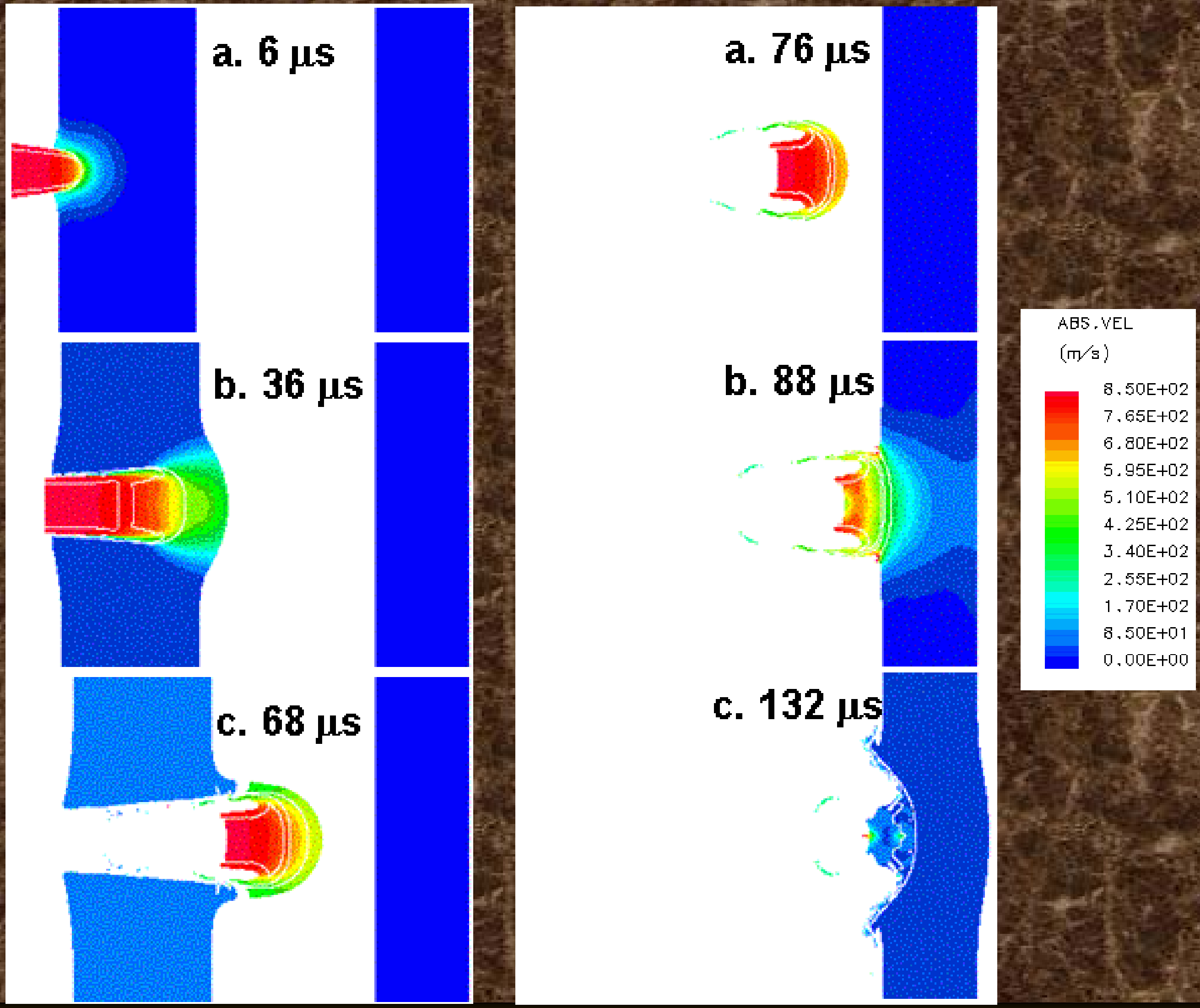
Color Represents Absolute Velocity



Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Color Represents Absolute Velocity

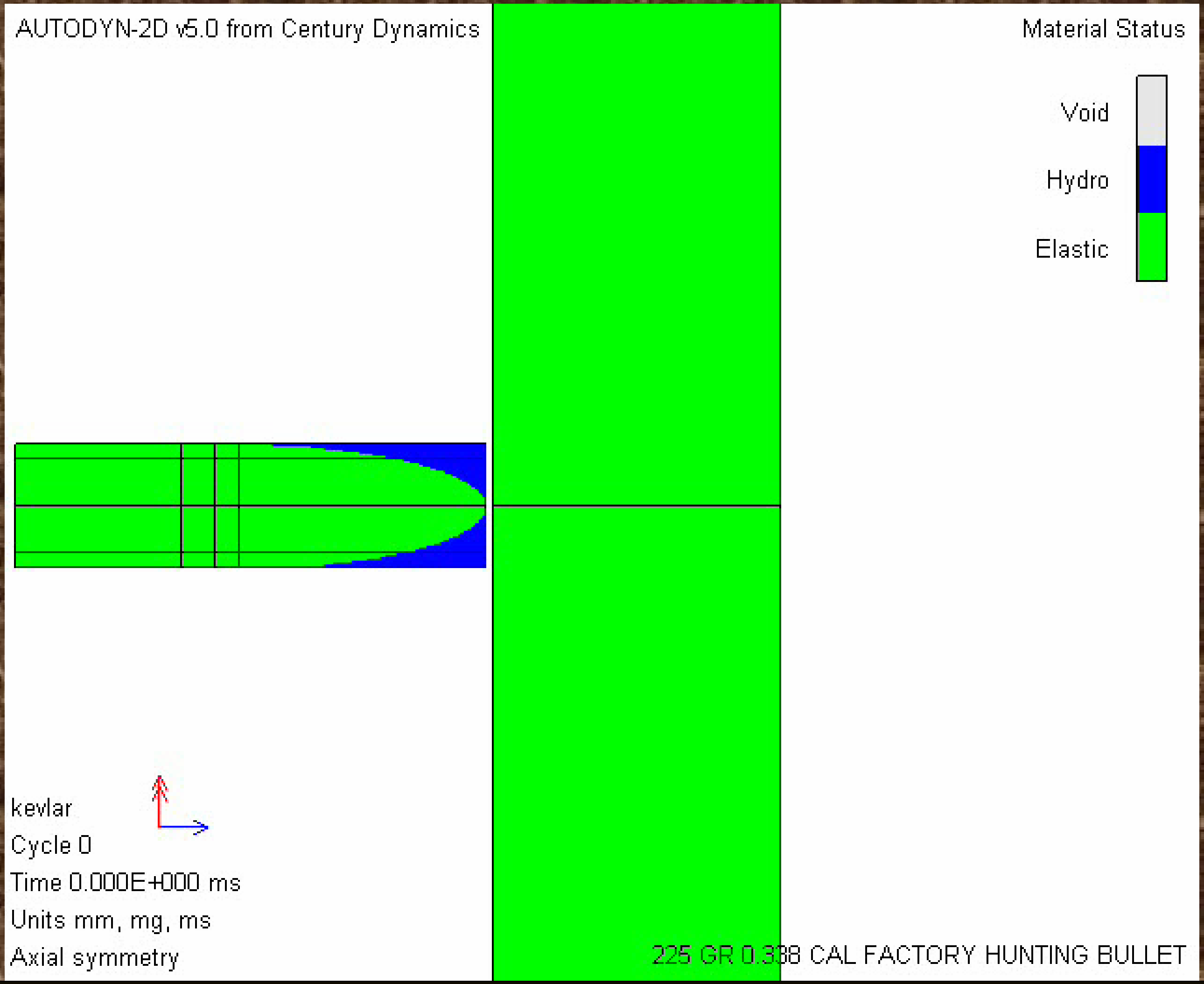
Eulerian Simulation



Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Color Represents Failure Mode

Lagrangian Bullet Transversely Isotropic Model



Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Color Represents Absolute Velocity

Lagrangian Bullet Transversely Isotropic Model

AUTODYN-2D v5.0 from Century Dynamics

Kevlar Model

225 Grain 0.338 Cal Hunting Bullet
Kevlar Board

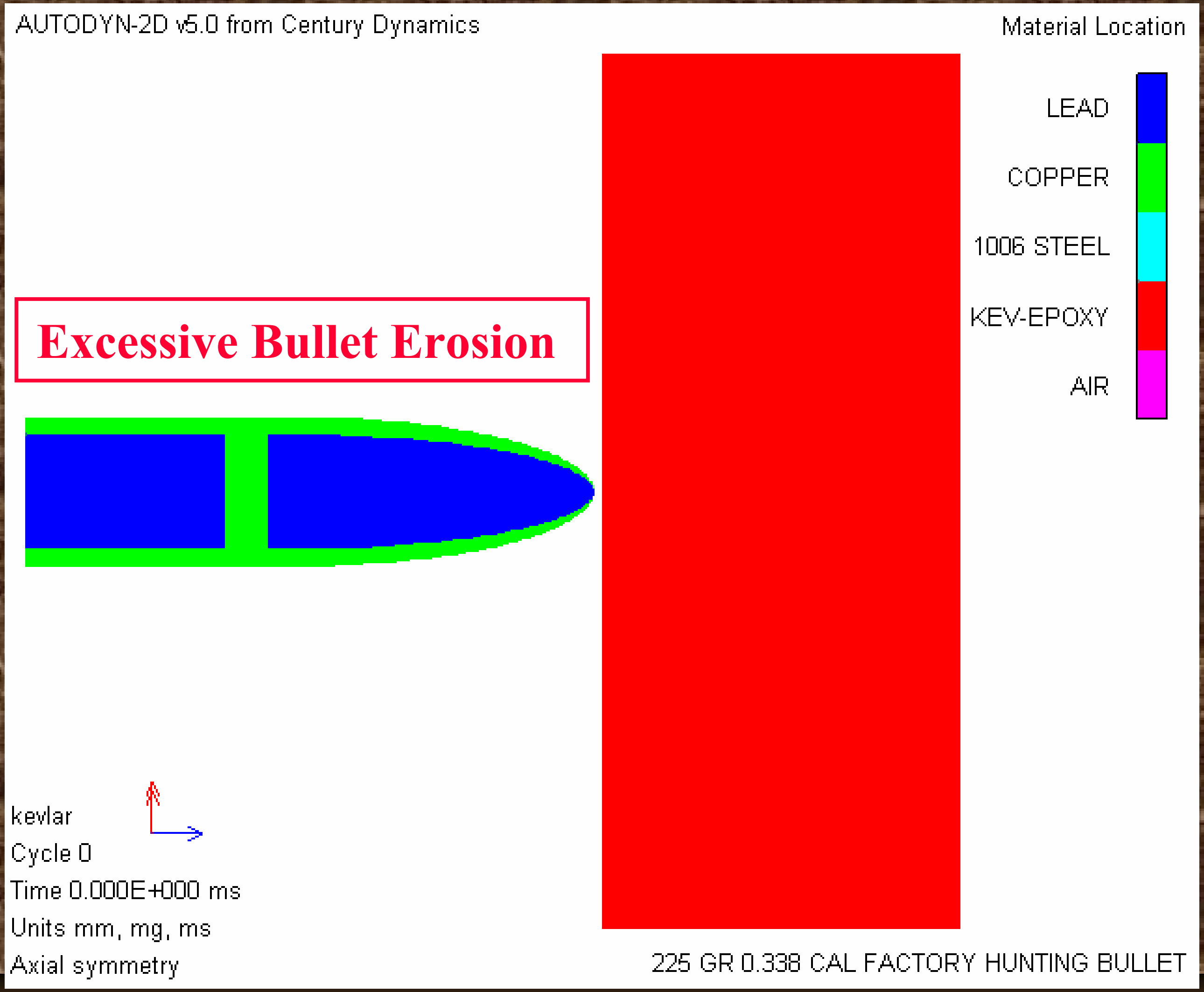
Sandia National Laboratories
Explosives Applications Department, Org 15322

Reasonable Bullet Erosion

Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

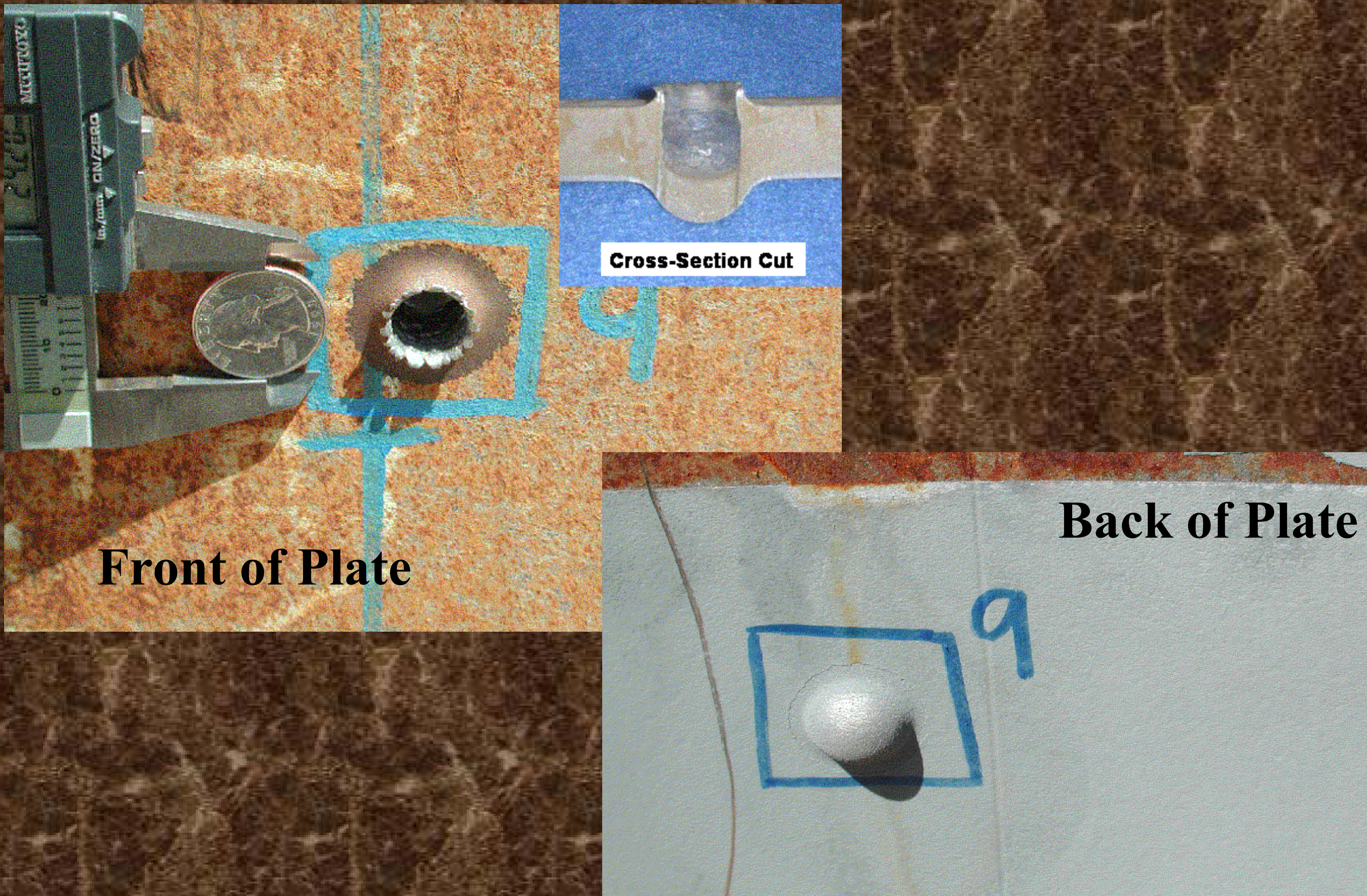
Color Represents Absolute Velocity

Lagrangian Bullet and Transversely Isotropic Kevlar Model

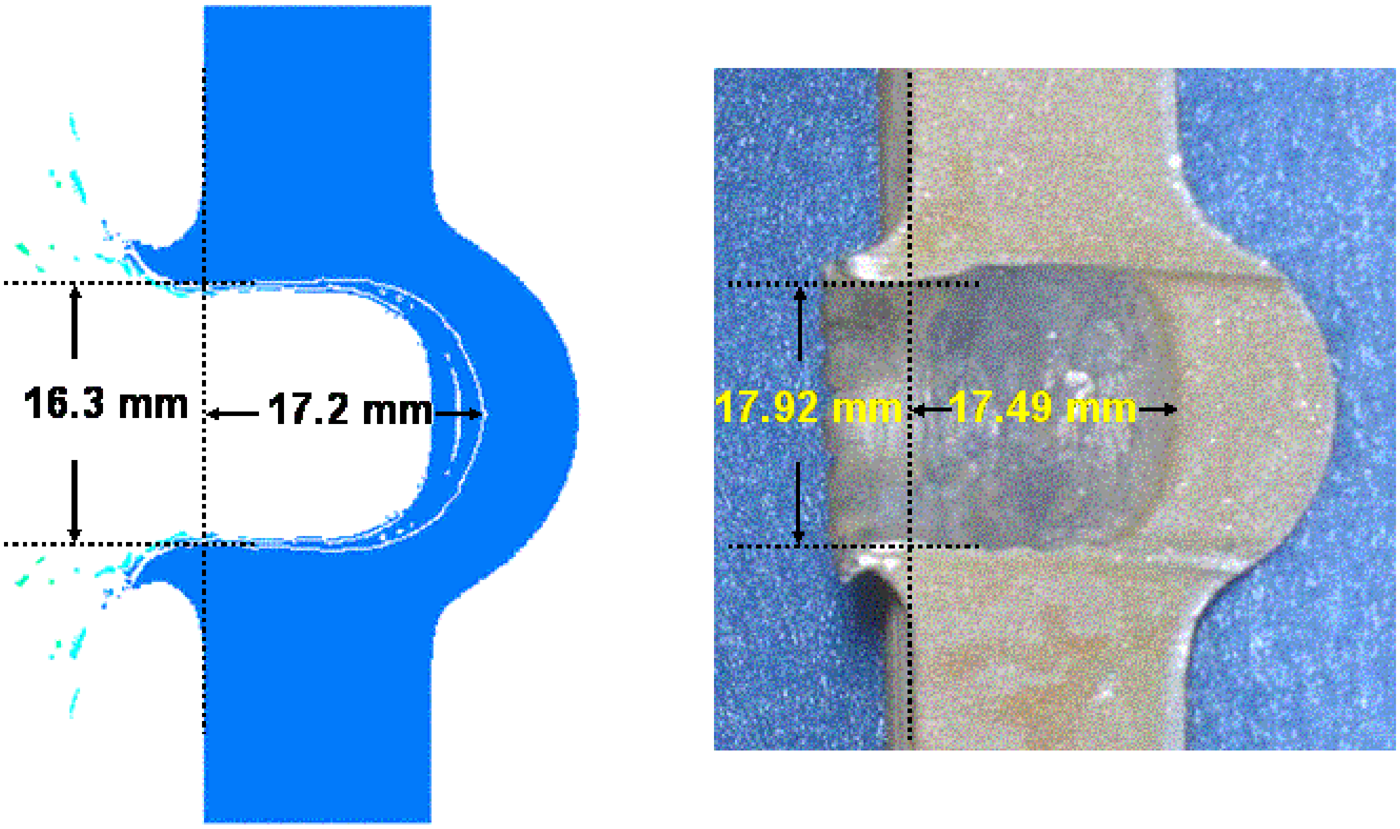


Ballistics Lab Results

Lead/Copper Bullet Impact on Steel

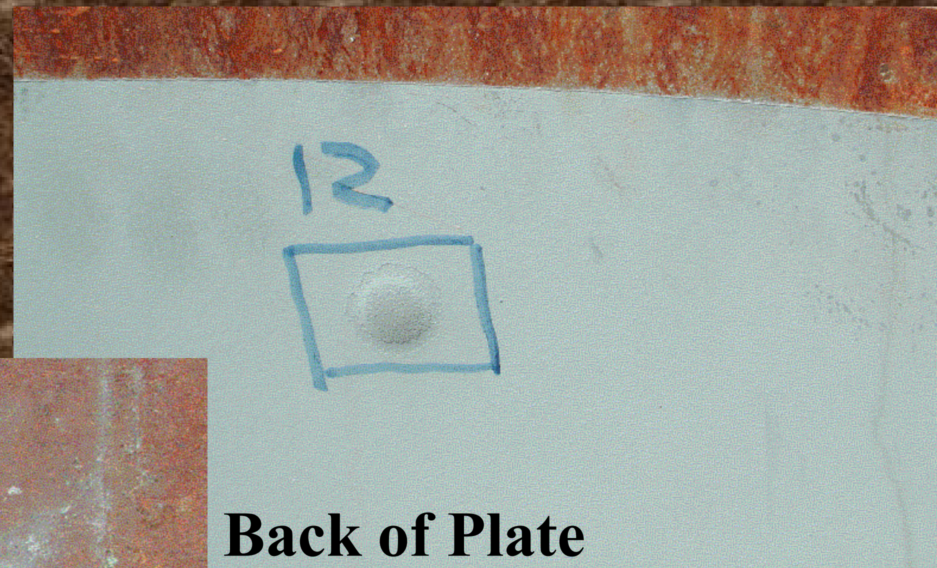


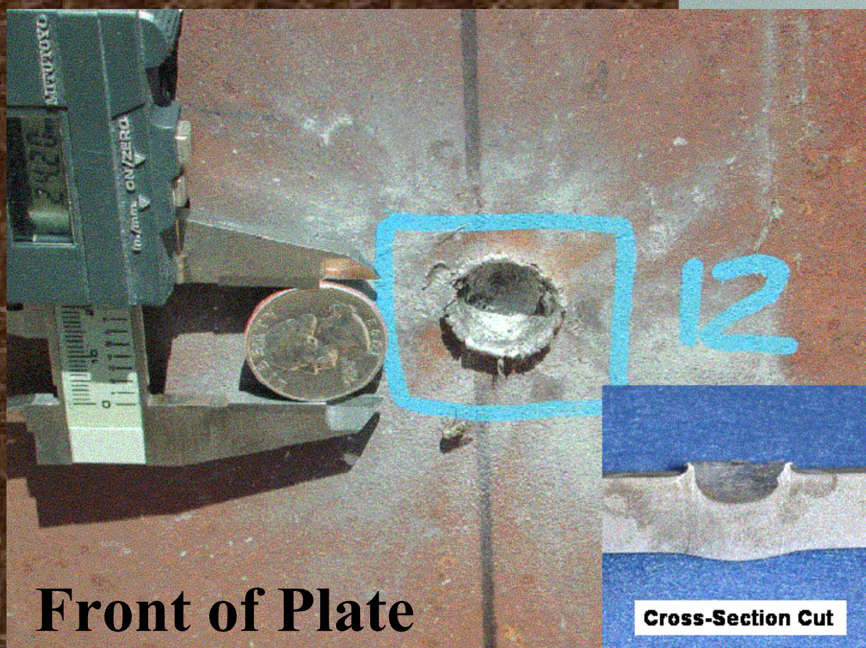
Comparison of Computer Predicted and Experimental Impact Crater – Steel Only



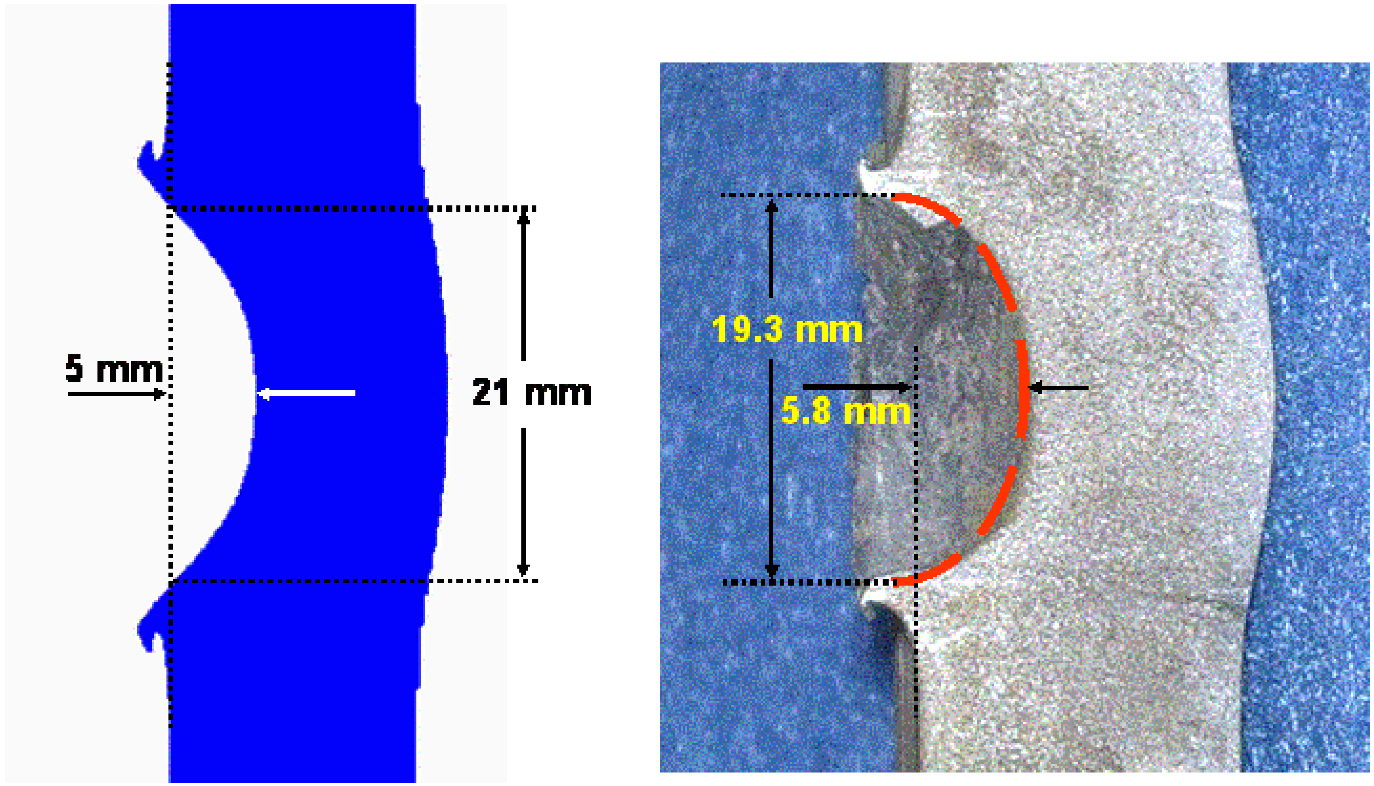
a. AUTODYN Simulation b. Shot 9 Cross-Section

Lead/Copper Bullet Impact on Kevlar® and Steel





Comparison of Computer Predicted and Experimental Impact Crater – Kevlar® /Steel

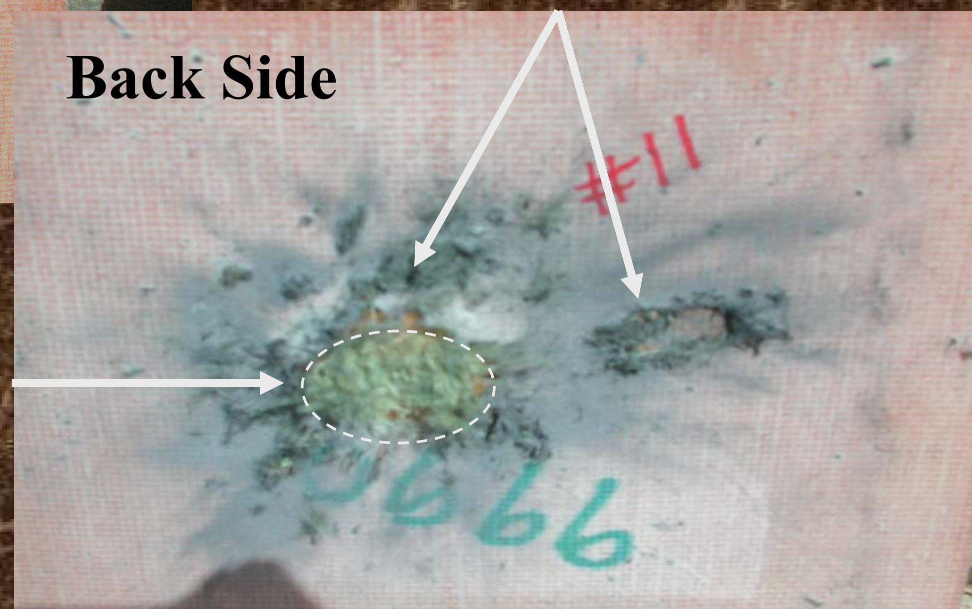


a. AUTODYN Simulation (Eulerian/Von Mises)

b. Shot 12 Cross-Section

Impact on Kevlar® Panel

Fragment Splatter
– Ricochet Back From Steel



Process Zone – Substantial Size

Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Eulerian Bullet - Lagrangian Transversely Isotropic Kevlar

Increased Kevlar Erosion – Leaves Too Much Bullet

Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Eulerian Bullet - Lagrangian Transversely Isotropic Kevlar

Reasonable Kevlar Erosion – Exiting Bullet About Right

Lead/Copper Bullet Penetration of Kevlar® and Mild Steel

Eulerian Bullet - Lagrangian Transversely Isotropic Kevlar

Course Mesh, High Kevlar Erosion – Exiting Bullet About Right

Conclusions

- Hydrocode and ballistics lab results match well for lead/copper A-Frame bullets impacting on mild steel.
- A reasonable match between hydrocode predictions and ballistics lab results is obtained for Kevlar® armor using a Von Mises strength model. This "engineering" model was used to complete the armor design.
- A Von Mises strength model misses some of the essential physics of bullet penetration into a transversely isotropic material like Kevlar®.
- Use of a Lagrangian transversely isotropic material model yields more consistent results for the Kevlar. However, modeling the lead/copper bullet is more appropriate in the Eulerian Frame of Reference.
- Simulations using an Eulerian Bullet and Lagrangian Kevlar have been attempted with reasonable success.
  - The results are dependent on the Kevlar erosion rate selected

$$\text{Fun} = \frac{\text{Novelty}}{\text{Work}}$$

Acknowledgments

- Dave Paul - Ballistics experiments at the 6750 gun site.
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